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Milk production Life Cycle Assessment: A comparison between estimated and measured emission inventory for manure handling

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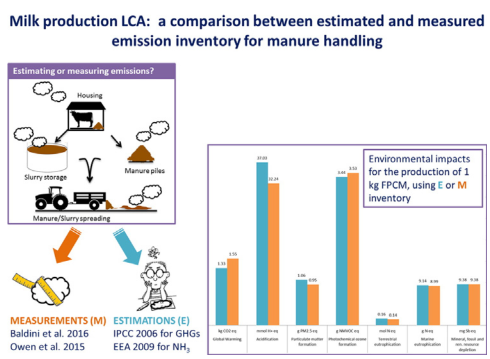
HIGHLIGHTS

- Housing emissions were measured from different manure removal systems.
- Measured or estimated emissions were used to compile life cycle inventory.
- Alternative data sources lead to different results.
- GWP impact seems to be underestimated by the IPCC equations.
- More flexible emission factors are needed to improve the accuracy of estimations.

GRAPHICAL ABSTRACT



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ABSTRACT

Measuring emissions from manure management operations (from the barns to the land) is a challenging task, subject to different uncertainties related to the spatial-temporal variability in the process leading to gaseous release. At the same time, emissions inventory is a prerequisite of Life Cycle Assessment (LCA) studies. Manure management emissions are usually estimated using equations developed by Intergovernmental Panel on Climate Change (IPCC, in the case of greenhouse gases emissions) and European Environmental Agency (EEA) for Nitrogen-related emissions. In the present study, the environmental impacts associated to three Italian dairy farms were calculated through a comparative LCA using two different approaches for complying the emission inventory. In the "estimated" approach (E) the commonly adopted IPCC and EEA equations were used, while in the "measured" approach (M) emissions actually measured were taken as input data to quantify the emissions associated to manure management. The results showed that the IPCC equation underestimates the manure management emissions, leading to a 10–42% lower global warming potential comparing E to M approach. On the other hand, ammonia related impact categories showed higher values if they were calculated using the estimated approach, underling that a safer level of estimation is maintained.

1. Introduction

The concept of *sustainability* has become a key driver in the last few years, steering the more recent political and socio economical choices. With the publication of "The livestock long shadow" in 2006, livestock's production in general, and in particular cattle, has been included among

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major responsible of environmental pollution and climate change. Since then, the awareness about emission reduction from livestock activities (GHG and other pollutants) has increased, resulting in a large number of researches focused on quantifying the environmental burden of milk production (O'Brien et al., 2012; van der Werf et al., 2014).

The environmental impact of livestock farming is strictly related to the emissions of methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3), arising from the manure management continuum (i.e. the animal housing, yards, manure storage and treatment, and land spreading (Chadwick et al., 2011)), and responsible for climate change, acidification and eutrophication effects, among other impacts. Gaseous losses from ruminant livestock in the form of manure management are responsible for 15.2% of agricultural emissions (Holly et al., 2017). Emissions of CH_4, N_2O and NH_3 may occur simultaneously from different sources: enteric fermentations and manure storages are the most important source of CH_4; while animal excreta in housing, manure storage systems and land application constitute the main source of N_2O and NH_3 (Hou et al., 2015).

Life Cycle Assessment (LCA) is a structured, comprehensive, international standardized and widely adopted method to assess the environmental impacts of a product or a process (Battini et al., 2014; O'Brien et al., 2014). LCA studies have four main pillars: the goal and scope definition; the inventory analysis; the impact assessment and the interpretation of results (ISO, 2006a). During the inventory phase, LCA practitioners refer to internationally recognized models to account for GHG and nitrogen emissions. The method proposed by Intergovernmental Panel on Climate Change (IPCC, 2006a, 2006b) is the most used (and recommended) for GHG estimation, while for NH_3 emissions, the most commonly selected reference are the equations developed by the European Environmental Agency (EEA, 2013) for the European area (Notarnicola et al., 2015). These models are based on emission factors (EFs) that were developed for the use in national GHG inventories, designed for the accounting at national scale (Nemecek and Ledgard, 2016). Their use for specific farming systems might be inappropriate, since the suggested EFs often do not take into account specific conditions of the investigated systems (Owen and Silver, 2015; Peter et al., 2016). Furthermore, recent researches indicate that the IPCC methodology may significantly underestimate CH_4 contributions from liquid dairy manure storage production, with discrepancies between inventory estimates and actual on-farm emissions (Baldé et al., 2016; Leytem et al., 2017; Lory et al., 2010).

Agricultural emissions are from nonpoint sources, characterized by high degree of variability due to climatic conditions, soil type, and agricultural practices (Goglio et al., 2017). For this reason, measuring emissions from manure management operations (from the barns to the land) is a challenging task, subject to different uncertainties related to the spatial-temporal variability in the process leading to gaseous release, which is strongly and complexly influenced by environmental conditions (Calvet et al., 2013; Owen and Silver, 2015). Despite the considerable efforts extended to measure gaseous emissions from natural ventilated buildings, measurement accuracy and standardization of methodology still are goals to be achieved (Takai et al., 2013).

Dairy system plays an outstanding role in the Italian context, but the high animal density characterizing the Northern regions pose a risk to the environment. The accurate estimation of the potential burdens associated to dairy farms is the first step for the identification of the best mitigation options that should be recommended to producers. In this context, manure handling systems play an important role, because different treatments and management strategies can alter manure composition, affecting GHG and NH_3 emissions from all the manure continuum (Holly et al., 2017).

The IPCC and EMEP/EEA equation are widely used for the estimation of emissions from the manure management. The aim of this work was to use two different data sources, field measurements or estimated emissions, to calculate the environmental impact associated to milk production in Italian dairy farms. In particular, results of LCA analysis conducted using the IPCC and EMEP/EEA equations for manure management were compared to the environmental impacts calculated using measured gaseous emissions. The use of these two different approaches for LCA calculation would allow to verify the degree of convergence of the methodologies applied for LCA and to underline their strengths and weakness. A Monte Carlo Simulation was also performed, in order to evaluate whether the two different approaches used for the LCA calculation could lead to different results even considering the high variability associated to measurements. Moreover, the impact caused by different animal categories (lactating or dry cows, heifers and calves) was investigated, to understand the contribution of the different physiological phases of animal growth to environmental burdens associated to milk production.

Results of the considered impact categories were separately discussed, highlighting differences achieved using the two calculation approaches (measured-M or estimated-E). The differences among impact associated to animal categories were underlined in a dedicated paragraph.

2. Materials and methods

2.1. Farms

For the present study three farms located in the North of Italy were monitored over one year (2015). The farms bred Holstein Friesians cows in permanent confinement. The main characteristics of the selected farms were resumed in Table 1. Farm 1 and Farm 2 can be considered of medium size for Italian conditions, as number of lactating cows and as arable land. Land was destined largely to cereal and annual forages. Farm 3, although smaller than the others, achieved a high production for cow.

In the three farms, the barns hosting cows had more consistent construction features, reflecting some farmer's management choices for manure handling, while higher variability was observed in barns where replacement herd lives. In particular, barns destined to cows were equipped with different flooring type and different manure removal systems, representative of the most common option spread in the Po Valley, as better described below.

Farm 1 was equipped with perforated concrete floor (holes diameter of 3.5 cm). The manure accumulated in the pit below the slatted surface and was periodically removed (approximately every 14 days). The cubicles were covered with rubber mats and were cleaned manually.

Farm 2 was equipped with flushing system. The feeding and the resting alley had a convex (1.5% slope) and inclined (3% slope) concrete surface, in order to increase the cleaning efficiency. The flushing was carried out twice a day with a flowrate of 0.15 $m^3\ s^{-1}$ for about ten minutes. The flush system utilized mainly recycled effluent from a screw press solid-liquid separator or occasionally water from the municipal water supply network. The cubicles were equipped with rubber mats and covered with the solid fraction derived from the manure separation system.

Farm 3 had solid floor covered with a rubber mat pavement. Manure was removed with delta scrapers running twice a day. The cubicles were equipped with straw and cleaned weekly.

2.2. Life Cycle Assessment

An attributional LCA was performed according to the ISO 14040 and 14044 standards (ISO, 2006a, 2006b), using the software Simapro PhD 8.4.0.0 (PRé Consultants, 2016).

2.2.1. Goal and scope definition

The aim of this study was to compare the environmental impact of three dairy farms with different manure handling options, using two different data set of emissions (measured or estimated emissions factors form manure management). The final scope was to verify the soundness

Table 1
Farm characteristics.

	Unit	Farm 1	Farm 2	Farm 3
Herd				
Lactating cows	n	450	300	110
Dry cows	n	110	45	20
Heifers (12–24 mo)	n	300	150	64
Heifers (6–12 mo)	n	150	90	30
Calves (<6 mo)	n	150	90	34
Yield per cow	kg milk yr^{-1}	11,111	9667	10,136
Livestock units	LU[a]	868	513	196
Replacement rate	%	25	30	24
Stocking rate	LU[a] ha^{-1}	8.35	3.29	3.93
Milk production intensity	t FPCM[b] ha^{-1}	48.3	19.3	22.5
Annual milk production	t FPCM[b]	5025	3009	1127
Annual meat production	t live weight	90	87	40
Land				
Farm land	ha	104	156	50
Alfalfa	ha			4.5
Barley	ha	10		
Maize	ha	50	100	16.5
Maize after ryegrass	ha	40		29
Meadow	ha		16	
Ryegrass	ha	40		29
Sorghum	ha		20	
Soybean	ha	4	20	
Triticale	ha	10		
Wheat	ha		40	
Land productivity				
Alfalfa, hay	t DM ha^{-1}			12.0
Barley silage	t DM ha^{-1}	10.6		
Maize, high moisture ear maize	t DM ha^{-1}	14.7	14.7	
Maize, silage	t DM ha^{-1}	16.5	20.2	14.9
Meadow, hay/silage	t DM ha^{-1}		11.7	
Ryegrass, silage	t DM ha^{-1}	8.4		9.0
Sorghum, silage	t DM ha^{-1}		12.3	
Soybean, grain	t DM ha^{-1}		3.8	
Soybean, silage	t DM ha^{-1}	4.2		
Triticale, silage	t DM ha^{-1}	12.5		
Wheat, silage	t DM ha^{-1}	13.4		
Purchased feeds				
Maize meal	t yr^{-1}	500		191
Soybean meal	t yr^{-1}	465	323	116
Sunflower meal	t yr^{-1}		206	6
Cotton seed	t yr^{-1}	168		
Molasses from sugar beet	t yr^{-1}	543		
Min&Vit supplements	t yr^{-1}	57	152	167
Straw	t yr^{-1}	482	179	11
Hay	t yr^{-1}	417	277	280
Other	t yr^{-1}	4591	270	
Manure handling system		perforated floor	concrete floor and flushing system	concrete floor and scraper

[a] LU: livestock unit (factors used for the calculation were: 1 for lactating cows; 0.8 for dry cows and heifers older than 2 years; 0.7 for heifers with age between 1 and 2 years old; 0.4 for calves and heifers younger than 1 year).
[b] FPCM: fat and protein corrected milk.

of the LCIA results, in order to verify the goodness of the estimation approach in catching differences between the management alternatives commonly adopted in dairy farms. Furthermore, to quantify the importance of replacement animals to the environmental impacts associated to each farm, the contribution of different age classes in which the herd is usually subdivided and managed was analyzed and discussed.

2.2.2. Functional unit, allocation, system boundaries

The environmental impacts of farms were evaluated using 1 kg of Fat and Protein Corrected Milk (FPCM) as functional unit (FU). The FAO (2010) correction formula was used to adjust the raw milk production to a quantity of milk with standardized quality (4.0% of fat and 3.3% of protein). Milk was considered as the main product of the farms and the biological allocation factor proposed by IDF (2010) was used to account for meat as co-product.

As described in the flow diagram drawn in Fig. 1, the analysis was conducted "from cradle to farm gate", considering as system boundaries all the on-farm processes (i.e. forages and crop production, fuel and electricity use, manure and livestock management) and the off farm processes linked to the production of external inputs (production of fertilizer and pesticides, fodders and bedding materials, feed concentrate, electricity and fuel, and associated transport). The study did not take account of farm personnel and of capital goods, such as buildings and machinery. Inputs such as medicines, detergents and disinfectants were excluded because their impact was estimated to be negligible (Ross et al., 2014). No account was made of carbon sequestration or loss resulting from land-use change in this study, since this is the current choice for standard footprinting methodology, because of a lack of scientific data at the world level (Daneshi et al., 2014; IDF, 2010).

The pathway was divided by farm activities (purchased materials, feed produced on farm, feed produced off farm, energetic consumptions and manure management) and then further divided by animal age classes (calves <6 mo, heifers 6–12 mo, heifers 12–24 mo, dry cows, cows) in order to understand the contribution of each animal category.

2.2.3. Life cycle inventory

Personal interviews with farmers were used in the data collection step. They provide details about cropping systems and field operations, fuel consumption, number of animals and housing systems, manure storage and animal diets. Questions about the inputs entering the farms were also posed, including amount of purchased feeds (both roughages and concentrates), fertilizers and pesticides, bedding materials, and number and origin of purchased replacement animals.

The amount of milk produced by each farm was provided by the farmers, whereas the amount of meat (as animal liveweight) was estimated on the basis of the number of animals sold for slaughter and their liveweight declared by the farmers.

2.2.3.1. Animal and farm operations

2.2.3.1.1. Animal diets. Information about specific diet of each animal category was collected. The CPM-Dairy Ration Analyzer Beta V3 software (Cornell-Penn-Miner, 2004) was used to estimate the key parameters of the diet composition (e.g. DM, CP, ether extract (EE), crud fiber, NDF, ADF and ADL, etc.). These parameters were used to calculate the gross energy intake and the digestibility of the diets according respectively to IPCC (2006a) and NRC (2001), and are summarised in Table 2. The composition of concentrate feed was estimated in the same way, using the raw materials reported in the commercial labels.

2.2.3.1.2. GHG emissions. CH_4 enteric emissions of each animal category were estimated starting from the gross energy of the feed diets, while CH_4 emissions from manure management were estimated using the volatile solids excretion calculated from the gross energy of the diets, following the Tier 2 IPCC (2006a) method.

N_2O emissions from manure, both direct and indirect, were calculated from the nitrogen excretion of the animals, as a result of the

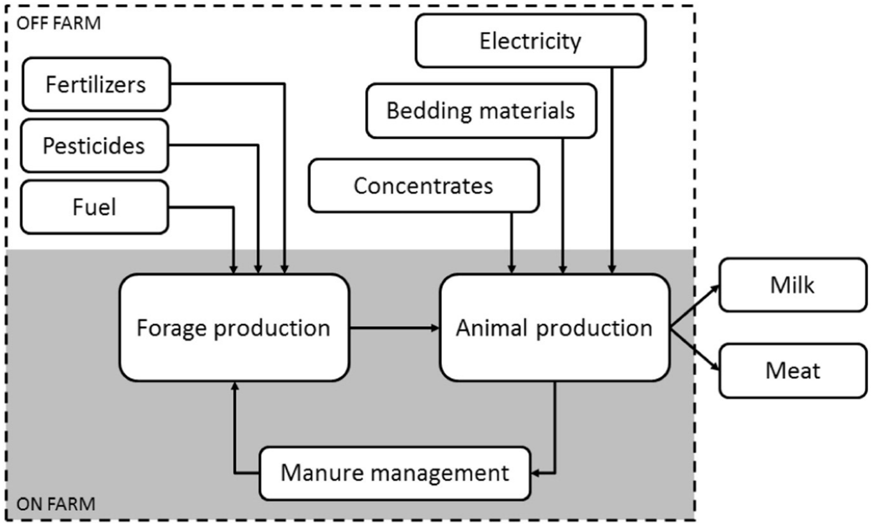

Fig. 1. System boundaries.

difference between the nitrogen intake and the nitrogen retained and excreted with milk (IPCC, 2006b).

CO_2 emissions from livestock respiration and manure were not accounted. It was assumed that they were balanced by the carbon previously absorbed and metabolized by crops composing the dairy diet, thus, being part of the carbon cycle, they not constitute an additional source of CO_2 (Holly et al., 2017).

2.2.3.1.3. Other emissions. NH_3 and NO_x emissions from farm operations were estimated according to the EEA method (EEA, 2013). The selected Tier 2 method starts from the nitrogen excreted by animals and applies a mass flow approach to calculate the NH_3 emissions, giving specific emission factors for each manure type (solid or slurry) and each step in the handling, expressed as a percentage of the NH_3-N content of manure.

CO_2 emissions from fuel combustion were estimated on the basis of fuel consumption declared by farmers.

The estimated emissions associated to animal and farm operations were reported in Table 3, disaggregated by animal category.

2.2.3.2. Measured emissions. The NH_3, CH_4, N_2O and emission factors arising from the cow barns of the selected farms were taken from Baldini et al. (2016). In that study, the emissions data were seasonally monitored over a global period of 27 months and acquired from different shed areas (i.e. feeding alley and cubicles). The concentration of the different gases was measured simultaneously by means of an Infrared Photoacoustic Detector (IPD; Bruel&Kjaer, multi gas monitor type 1302) and subsequently elaborated to obtain the emission factors expressed as mg m^{-2} h^{-1}.

Measured emission factors were used as reference for the calculation of the GHG and NH_3 emissions from the barns of each farm (Table 4).

Storage emissions of CH_4 and N_2O were calculated using the data reported by Owen and Silver (2015). Reviewing published researches on field-scale measurements of GHG emissions from dairies, they provided average emission rates (kg $head^{-1}$ $year^{-1}$) for CH_4, N_2O and CO_2 from different kind of slurry storages. These figures were used in order to fill the gap between estimated emissions and the field measured emissions: in fact the IPCC approach uses "combined" emission factors, that do not allow to distinguish between emissions from the barns and the storage. For NH_3 this step was not necessary, since EEA equations allow to separate emissions arising from different steps of manure handling.

2.2.3.3. External inputs. Off-farm activities related emissions were modeled using Ecoinvent® 3.3 database (Ecoinvent, 2016). The considered processes included the production chain of commercial feed (from crop growing to feed factory processing), production of purchased forages and bedding material, production of chemical fertilizers and pesticides, and diesel and electricity used in the farms. Transportation was also accounted, considering an average distance between farms and feed producers of 150 km, using a 16-32 t lorry. The origin of the feed was taken into account (Italy, Europe, and extra Europe).

2.2.3.4. Land operations. The NH_3 and NO_x arising from manure and synthetic fertilizers application were estimated using the equations of EEA (2013). Direct and indirect N_2O losses from fertilizer application were estimated following respectively the Tier 2 and Tier 1 methods suggested by IPCC (2006b), accounting in the estimation the amount of

Table 2
Animal diets parameters.

Diet	Farm 1					Farm 2					Farm 3				
	LC	DC	H12–24	H6–12	C < 6	LC	DC	H12–24	H6–12	C < 6	LC	DC	H12–24	H6–12	C < 6
DMI (kg day^{-1})	25.90	10.20	11.2	4.60	6.08	22.56	8.76	6.13	3.39	4.53	20.9	10.52	10.65	6.18	6.08
CP (% DM)	15.83	9.77	9.70	9.75	18.01	17.44	13.11	13.11	13.02	20.51	16.39	12.49	14.78	18.05	18.01
NDF (% DM)	33.69	49.99	50.67	50.31	41.76	29.30	51.42	51.42	51.52	35.03	29.80	52.75	48.23	43.81	41.76
ADF (% DM)	21.54	32.27	32.00	32.41	32.58	18.84	31.87	31.87	31.94	21.27	19.28	37.90	35.78	31.77	32.58
EE (% DM)	3.45	2.64	2.51	2.62	2.94	3.85	3.17	3.17	3.14	2.81	3.30	3.07	2.94	2.83	2.94
NFC (% DM)	42.66	30.06	31.48	29.78	27.14	46.16	27.52	27.52	27.53	36.64	40.82	22.01	25.77	25.01	27.14
Ash (% DM)	6.17	8.92	7.7	8.91	14.11	4.91	6.44	6.44	6.44	6.95	12.78	13.32	11.58	13.89	14.11

LC: lactating cows; DC: dry cows, H12–24: heifers 12–24 months; H6–12: heifers 6–12 months; C < 6: calves <6 months.
DMI: Dry matter Intake; CP: Crude Protein; NDF: Neutral Detergent Fiber; ADF: Acid Detergent Fiber; EE: Ether Extract; NFC: Non Fiber Carbohydrates.

Table 3
Estimated emission from animals and farm operations disaggregated by animal categories and expressed as kg of gas $head^{-1}$ $year^{-1}$.

Emissions	Farm 1					Farm 2					Farm 3				
	LC	DC	H12–24	H6–12	C < 6	LC	DC	H12–24	H6–12	C < 6	LC	DC	H12–24	H6–12	C < 6
CH_4 enteric	143.38	52.25	56.82	37.67	24.29	128.96	50.86	55.46	35.78	20.96	132.31	56.51	57.65	34.95	23.67
CH_4 manure management	63.13	3.06	5.81	2.63	5.76	153.35	37.32	70.70	1.85	1.11	33.61	12.73	16.84	4.98	3.36
N_2O dir	0.62	0.19	0.15	0.16	0.44	0.00	0.00	0.00	0.00	0.00	1.13	0.60	0.69	0.46	0.22
N_2O ind	0.87	0.15	014	0.11	0.30	0.00	0.25	0.19	0.13	0.32	0.99	0.45	0.61	0.35	0.17
NH_3 housing	20.89	19.82	15.59	19.93	20.45	20.98	21.95	20.98	20.98	19.93	20.98	20.35	20.98	20.35	22.94
NH_3 storage	18.54	12.71	17.19	22.78	20.48	18.18	12.53	18.18	18.18	22.78	18.18	20.91	18.18	20.91	7.93
NO_x	0.13	0.31	0.99	1.49	0.75	0.02	0.01	0.02	0.02	1.49	0.02	0.89	0.02	0.89	0.26

LC: lactating cows; DC: dry cows, H12–24: heifers 12–24 months; H6–12: heifers 6–12 months; C < 6: calves <6 months.

nitrogen applied to soils both from synthetic fertilizers and from manure (slurry and solid) plus the nitrogen from crop residues.

Emissions occurring during field operations (i.e., plowing, harrowing, sowing, harvesting, etc.) were estimated using the processes of the Ecoinvent® 3.3 database (Ecoinvent, 2016).

Concerning emissions to water, the amount of nitrogen leached was estimated following the IPCC (2006b) model, while the emissions of PO_4^{3-} were calculated considering the amount of phosphorus drained away with water (run-off) and leached, as proposed by Nemecek and Kägi (2007).

For accounting purposes, the emissions that occurred after the land application of manure were assigned to the production of crops given that manure was used as a nutrient source.

2.2.4. Life cycle impact assessment

In order to understand the effect of different data sources used in this study on the potential impacts associated to a dairy farm, the following impact categories and technical quantities were evaluated per 1 kg of FPCM:

a. Global Warming, kg CO_2 eq
b. Acidification (A), mmol H^+ eq
c. Particulate matter formation (PMF), g $PM_{2.5}$ eq
d. Photochemical ozone formation (POF), g NMVOC eq
e. Terrestrial eutrophication(TE), mol N eq
f. Marine eutrophication (ME), g N eq
g. Mineral, fossil and renewable resource depletion (RD), mg Sb eq

The assessment was performed at midpoint using methods recommended by ILCD Handbook (IES, 2012). This shortlist of current best characterization methods represents the big effort to reach a higher level of standardization among LCA studies, undertaken by the European Joint Research Center. To make easier comparison with literature, in some case (for acidification and eutrophication impact categories) the potential impacts were recalculated using the CML method (Guinée et al., 2002). Indeed, LCA studies related to milk production are frequently performed using this method to conduce the LCIA (Baldini et al., 2017).

Table 4
Comparison between estimated (E) and measured (M) emissions from manure management for lactating cows. Data were disaggregated by source (dairy barns or slurry storage) and expressed as kg of gas $head^{-1}$ $year^{-1}$.

		CH_4		N_2O dir		NH_3	
		Dairy barns	Storage	Dairy barns	Storage	Dairy barns	Storage
Farm 1	E	63.13		0.62		20.90	18.54
	M	2.17	101[a]	0.05	0.3[a]	1.24	18.54
Farm 2	E	153.35		0.00		20.98	18.18
	M	1.11	368[a]	0.02	0.9[a]	0.40	18.18
Farm 3	E	33.61		1.13		20.98	18.18
	M	5.84	101[a]	0.19	0.3[a]	2.48	18.18

[a] Data taken from Owen and Silver (2015).

A Monte Carlo Simulation was performed in order to assess to what extent the uncertainties related to the measured data (CH_4, N_2O, NH_3 housing emissions) used in the study can influence the observed environmental impacts. The analysis was conducted with a confidence interval of 95% and 1000 iterations.

3. Results and discussion

Table 5 shows environmental impacts evaluation of milk production in three dairy farms using estimated (E) or measured (M) emissions arising from manure handling.

3.1. Global warming

For global warming impact category, the results ranged from 1.11 to 1.69 kg CO_2 eq kg^{-1} FPCM and were aligned with values reported by Italian researchers (Bacenetti et al., 2016; Battini et al., 2014; Bava et al., 2014; Guerci et al., 2013). The measured emissions led to increment the global warming potential (M/E: 4% for Farm 1, 42% for Farm 2, 10% for Farm 3).

This result was due to the higher quantity of CH_4 emissions from manure directly measured compared to CH_4 estimated through IPCC equations. Measured CH_4 emissions were always higher than estimated ones (see Table 4). This difference constituted the main cause leading to the increased global warming impact in the calculation approach using measured emission factors. The influence of N_2O emissions was limited. Indeed, they increased only in Farm 2, while in other farms measured emissions were lower than estimated ones. This was confirmed also by the contribution analysis for this impact category, which attributed to CH_4 the largest share of the impact contribution (50%), followed by CO_2 (37%) and N_2O (18%), using 1, 25, 298 CO_2 equivalent as characterization factors for 100-year time horizon for CO_2, CH_4 and N_2O respectively (IPCC, 2007).

Differently from field studies, frequently focused on the quantification of emissions from a particular stage of the manure management continuum, the IPCC estimations are based on "combined" emission factors that join together emissions arising from barns and storage. As regarding CH_4, IPCC estimations are function of Volatile Solids (VS) excreted by animals and thus loaded in the management system, the maximum CH_4-producing capacity of the manure (B_0), and CH_4 conversion factors (MCFs, defining the percentage of the B_0 achievable with the selected manure management system). The choice of the proper MCF is crucial for the representativeness of the final result, due to their broad variation also within the same climatic zone. Furthermore, MCFs cannot reflect the variety of possible solutions for manure treatment and are grouped in generic categories poorly defined.

In the case of direct N_2O emissions, the IPCC equation reflects the amount of N excreted by the animal categories corrected for an emission factor (named EF_3). The EF_3 is equal to zero for uncovered anaerobic lagoons, but our data do not support this result.

As outlined by Battini et al. (2014) the second main contributor to total GHG emissions, after enteric emissions, are storage emissions. However, they have a high degree of variability and are rarely

Table 5
Potential environmental impacts associated to the three selected farms, calculated with estimated (E) or measured emissions (M) and expressed per kg of FPCM.

Impact category	Unit	Farm 1		Farm 2		Farm 3	
		E	M	E	M	E	M
Global warming	kg CO_2 eq	1.62	1.69	1.11	1.58	1.26	1.38
Acidification	mmol H^+ eq	45.73	40.96	33.84	28.60	31.52	27.17
Particulate matter formation	g $PM_{2.5}$ eq	1.44	1.33	0.84	0.73	0.89	0.79
Photochemical ozone formation	g NMVOC eq	5.65	5.68	2.14	2.33	2.53	2.59
Terrestrial eutrophication	mol N eq	0.18	0.16	0.15	0.13	0.14	0.12
Marine eutrophication	g N eq	14.91	14.76	6.23	6.07	6.27	6.14
Mineral, fossil and ren. resource depletion	mg Sb eq	17.99	17.99	3.83	3.83	6.31	6.31

experimentally measured. Battini et al. (2014) conducted a sensitivity analysis and demonstrated that the range of results found in many studies could be simply explained by the variation of this parameter. Therefore, they pointed out that additional experimental results quantifying storage emissions from manure and digestate management are essential in order to have a precise picture of GHG emissions from dairy farms.

A recent study conducted by Aguirre-Villegas and Larson (2017) highlights the key role of manure management in GHG emission reductions. The authors investigated how management practices and manure treatments affect emissions, identifying storage systems as weak points of the manure-handling continuum, and underling the importance of storage covers to reduce emissions.

3.2. Acidification

The acidification potential ranges from 27.17 to 45.73 mmol H^+ eq kg $FPCM^{-1}$.

As outlined by results reported in Table 5, calculations ran using estimated emission factors resulted in higher acidification potential in all the selected farms. The rank among farms observed in Table 4 was consistent with LCIA results. However, EEA equations resulted in greater estimation of NH_3 emissions of about 50%, while the difference observed among measured and estimated LCIA results was narrow (M/E: −10% for Farm 1, −16% for Farm 2, −14% for Farm 3; Table 5). Indeed, despite its high share of contribution, manure management was not the only factor affecting this impact category. Contributions to acidification were spilt among feed production (both on and off farm), with a share of 31–57%, and manure management operations, for the remaining 42–66%, while a small proportion of acidification can be attributed to energy consumption and purchased materials (Fig. 2).

Farm 1 showed the higher impact compared to other farms. This value was mainly due to the higher proportion of feed produced off farm. For this farm, the main substances contributing to acidification were ammonia and sulfur dioxide with the 77% and 15% respectively (average of M and E). On the other hand, Farm 2 and 3 showed similar acidification potentials, and the ammonia and sulfur dioxide contributes to acidification were 92% and 4% on average. The high contribute of sulfur to acidification observed in Farm 1 may be due to a particular pesticide used by the farmer, containing high concentration of this element.

The values reported for this impact category, recalculated according to the CML method for comparative purposes, were in line with those observed in literature (Castanheira et al., 2010; Guerci et al., 2013; Meul et al., 2014), apart from Farm 1, to which were associated high level of acidification as previously outlined (Table 6). Furthermore, also Battini et al. (2016) found that the acidification potential was mainly caused by NH_3 emissions from animal housing and from fertilizer application to the soil, but also by sulfur dioxide and nitrogen oxides from diesel combustion.

3.3. Particulate matter formation

The particulate matter formation ranged between 0.73 and 1.44 g $PM_{2.5}$ eq kg $FPCM^{-1}$ and differences were observed between calculations made using estimated or measured emissions (M/E: −8% for Farm 1, −14% for Farm 2, −11% for Farm 3). The higher impact was associated to Farm 1, while the potential impacts of Farm 2 and 3 showed lower values.

Farm activities that mainly contribute to this impact category were feed produced both on and off farm and the manure management operations, but with different percentage among farms. In Farm 1, where the amount of required feed is bigger (see Table 1), the contribution of auto-produced and purchased feed was respectively 35% and 32%, while the manure management accounts for 31% (average values among E and M). Otherwise, in Farm 2 and 3 the biggest contribution was associated to manure management operations (from 46 to 54%) while feed production accounted for a maximum of 28% (both on farm and off farm).

Particulate matter is strictly dependent from ammonia emission (Backes et al., 2016). Indeed, NH_3 is involved in reactions with sulfuric and nitric acid that lead to the formation of secondary inorganic particulate matter. This was confirmed by the high shares of impact contribution attributable to NH_3 (from 52% of Farm 1 M to 84% of Farm 2 E), in accordance to results previously reported by Battini et al. (2014). Direct emission of particulate matter ranged from 10% (Farm 2 E) to 21% (Farm 1 M and Farm 3 M).

3.4. Photochemical ozone formation

The photochemical ozone formation ranged from 2.33 to 5.68 g NMVOC eq kg $FPCM^{-1}$. E and M calculation approaches resulted in slightly different impact estimation (M/E: 0.5% for Farm 1, 9% for Farm 2, 2% for Farm 3).

The feed produced off-farm was the major contributor of this impact category, with a share ranging from 57% to 73%. Among the major species responsible of POF there were NO_x (63% on average), followed by NMVOC compounds (10% on average). However, the major differences among farms were observed in the contribution given by CH_4, ranging from 4% (Farm 1 E) to 21% (Farm 2 M).

Important contribution due to CH_4 emissions were reported also by González-García et al. (2013). Our results were in line with values reported by Battini et al. (2014), but they were higher compared to those referred to the farm subsystem in studies evaluating the UHT milk production (Castanheira et al., 2010; Djekic et al., 2014; Fantin et al., 2012) (Table 6).

3.5. Terrestrial and marine eutrophication

The impact on eutrophication was divided into two categories: terrestrial and marine.

For terrestrial eutrophication, significant percentage of variation between M and E calculation approaches were observed (M/E: −12% for Farm 1, −16% for Farm 2, −14% for Farm 3). Farm 1 showed the highest impact compared to other farms, due to the highest contribution of feed produced off-farm (29% for Farm 1, compared to 13% and 9% of Farm 2 and 3 respectively, average values).

Ammonia was the major contributors for this impact (93% on average) followed by NO_x (7% on average).

Fig. 2. Potential environmental impacts associated to the three selected farms, contribution of farm activities.

As regarding marine eutrophication, the results did not highlight important differences between M and E calculation approaches (M/E: −1% for Farm 1, −3% for Farm 2, −2% for Farm 3).

Feeds produced off farm gave the highest contribution to this impact category, ranging from 51% of Farm 3 E to 81% of Farm 1 M. This is partially in contrast to what previously observed by Battini et al. (2014),

Table 6
Comparison among acidification, eutrophication and photochemical oxidation impacts reported in literature and those obtained in the present study using CML as life cycle impact assessment method.

Reference	FU	LCIA method	Acidification potential	Eutrophication	Photochemical oxidation
			(kg SO_2 eq)	(kg PO_4^{3-} eq)	(kg C_2H_4 eq)
Present study	FPCM	CML	15.14–27.26	5.8–11.3	0.31–0.52
Arsenault et al., 2009	raw milk	CML	9.6	3.17	0.23
Bacenetti et al., 2016	FPCM	EPD	6.5	2.95	0.75
Bava et al., 2014	FPCM	EPD			
Castanheira et al., 2010	raw milk	CML	20.41	7.04	0.19
Djekic et al., 2014	UHT milk	CCaLC			0.26
Fantin et al., 2012	HQ milk	CML			0.32–0.35
González-García et al., 2013	ECM	CML			0.27
Guerci et al., 2013	ECM	EPD	7.44–25.64	4.61–11.12	
Meul et al., 2014	FPCM	CML	11.26–15.62	3.7–4.3	
Nguyen et al., 2013	FPCM	CML	9.85–12.09	4.37–5.05	
van der Werf et al., 2009	FPCM	CML	7.6	7.1	

who reported a high share of field emissions contributing to this impact category, and may be due to the lower amount of feed purchased in the farm studied by those authors, compared to the farms investigated in this study. Nitrate was the species that mainly contribute to marine eutrophication, ranging from 75% (Farm 3 E and Farm 2 E) to 82% (Farm 1 M). Major differences were observed in ammonia contribution: 7% for Farm 1, 15% for Farm 2, 13% for Farm 3 (average values). This may be due to the characterization factor given to NH_3 in the ILCD method (Goedkoop et al., 2009) that is higher than the factor given to NO_3^{2-} (0.824 and 0.226 respectively).

Most of the studies found in literature use the CML method (Heijungs et al., 1992) to account for eutrophication potential. Impact assessment recalculated using this alternative method leads to results in accordance with the values obtained by other researchers (Bava et al., 2014; Nguyen et al., 2013; van der Werf et al., 2009).

3.6. Mineral, fossil and renewable resource depletion

Results for mineral, fossil and renewable resource depletion ranged from 3.83 mg Sb eq kg FPCM^{-1} to 17.99 mg Sb eq kg FPCM^{-1}. These values were comparable to those obtained in the farm subsystem by Hospido et al. (2003), but they seemed quite low if compared to other literature data (Arsenault et al., 2009; Castanheira et al., 2010; González-García et al., 2013).

In all the considered farms, resource depletion is mainly due to feed production on farm land and outside of dairy farm with values from 91 to 99%. The highest estimations for this impact category expressed per kg of FPCM was associate to Farm 1, as a consequence of the high quantity of feed purchased.

3.7. Monte Carlo Simulation (MCS)

Uncertainty analysis of the measured data was carried out using Monte Carlo statistical methodology. Generating thousands of random samplings of the input data, MCS propagates the uncertainties throughout the LCA model and gives a probabilistic distribution of the predicted impacts (Chen and Corson, 2014). In this case, a comparative analysis was carried out to understand whether the LCA conducted using the different approaches described in this study (measured vs estimated data) lead to different results, even considering the high variability associated to measurements.

Fig. 3 shows the graphical results of the uncertainty analysis for the comparison between environmental impact assessment of 1 kg of FPCM, using measured data (M) or estimated (E) for manure management emissions. For each indicator, the blue bar represents the probability that environmental impact calculated using estimated data could result higher than the impact calculated using measured data (E ≥ M), while the orange bar represents the opposite (E < M).

The uncertainty analysis confirmed that environmental impacts calculated using measured data (M) resulted lower than estimated (E) for acidification, particulate matter, terrestrial and marine eutrophication (level of statistical significance >99.9%). These results underlined that gas emissions measurements, despite its variability, lead to significantly different environmental impact estimations.

3.8. Contribution of different animal categories

3.8.1. Lactating and dry cows

Lactating cows were responsible of the largest contribute to all impact categories considered in the study (Fig. 4). Compared to other animal categories, lactating cows were the larger emitters of GHGs, giving the highest contribute to climate change, ranging from 58 to 83% of the kg CO_2 eq kg FPCM. The number of animals and the higher feeding requirements, resulting in a larger feed consumption (both purchased and produced on farm), and the significant contribution of enteric fermentation were major responsible of the high share of global warming attributable to cows.

Farm 2 had the largest number of dairy cows, as percentage of the total herd (44.4% Farm 2; 42.6% Farm 3 and 41.5% Farm 1), this caused higher impacts of these animals on total farm global warming (79%). Instead, Farms 1 and 3 had similar percentage of dairy cows but their contribution was different, 59% for Farm 1 and 68% for Farm 3.

Dry cows contributed to global warming for 4–9%. The highest contribution was found in Farm 1, where the percentage of dry cows on the total herd were 10% (7% Farm 2 and 8% Farm 3). During dry period, usually lasting 60 days, cows still contribute to overall emissions of CH_4, NH_3 and other pollutants but they are not milked. From an environmental point of view, this period is quite crucial: if it is too long farm annual

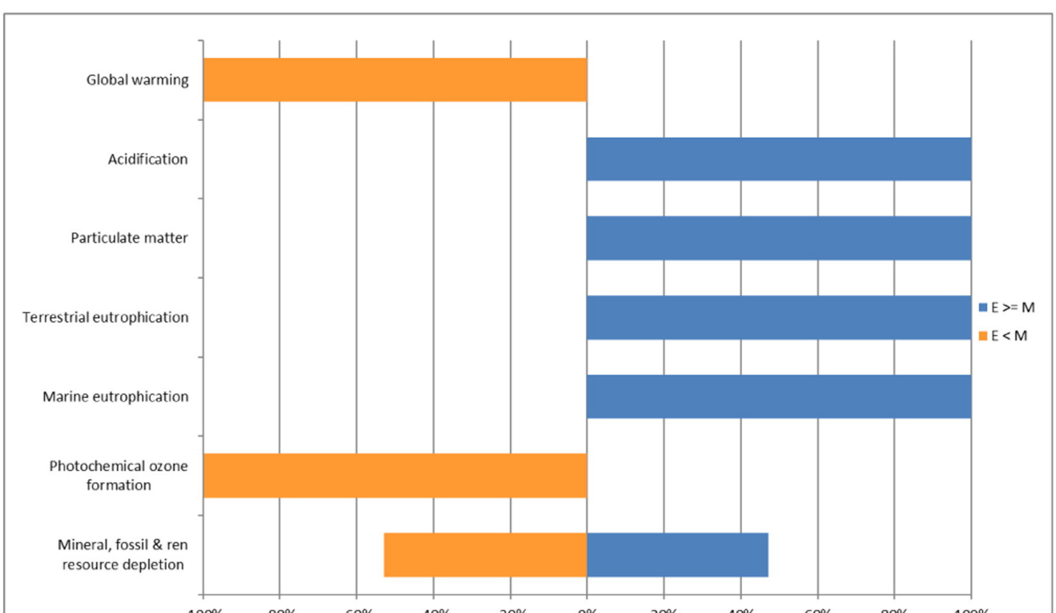

Fig. 3. Results of the uncertainty analysis for the comparison between LCA results using estimated (E) and measured emissions (M) for the evaluated impact categories.

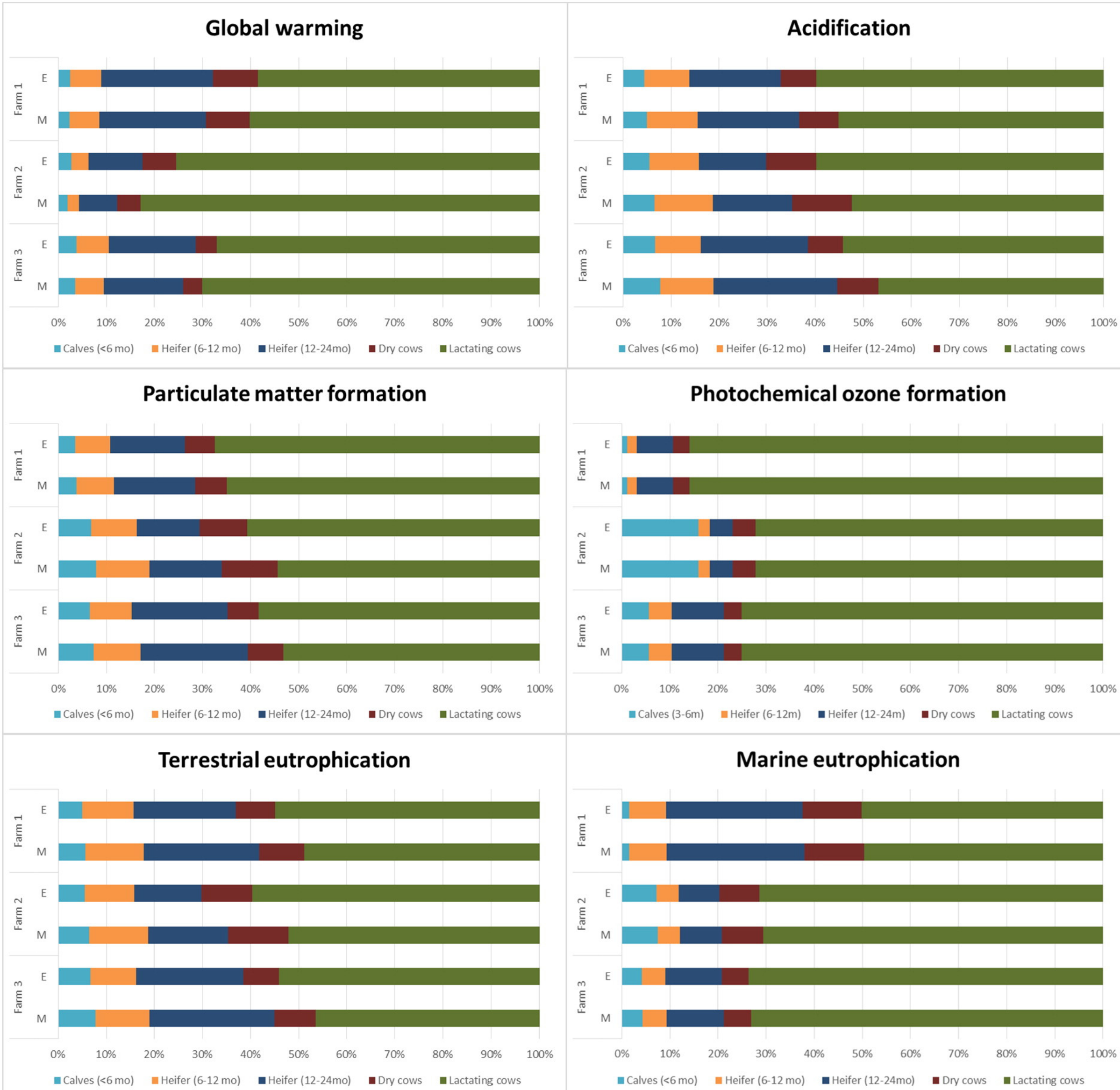

Fig. 4. Potential environmental impacts associated to the three selected farms, contribution of different animal categories.

milk production decreases and the environmental impacts per unit of product increase.

Lactating cows contributed for 47–57% on acidification, as a consequence of NH_3 emission from manure and feed production (ON and OFF farm). For the other impact categories, lactating cows' contribution changed from 46 to 86%; the highest value was found in resource depletion, due to the high values of energy needed to produce feed for lactating period.

3.8.2. Heifers and calves

On average 49% of the herd was represented by heifer (from 6 to 24 months) and calves (<6 months). This data was almost the same in the three farms, but the contribution of these animal categories to the environmental impacts were quite different among farms.

For global warming, heifer and calves contribution ranged from 12 to >30%. Heifers from 12 to 24 months are major responsible of this figures. This growing phase is crucial for the success of the whole production system, since in this period is usually preformed the first insemination of the heifers. If management problems occur, the age of first calving is postponed and the unproductive period becomes longer. Management choices could increase reproduction efficiency in this phase in order to optimize parameters, such as heat detection rate and pregnancy rate. From an environmental point of view, these operational parameters would decrease the unproductive period and increase milk production. Indeed, as suggest by de Boer et al. (2011) improving fertility of the herd would reduce net GHG emissions, because fewer animals, and hence less feed, are needed to produce the same amount of product.

For environmental impact categories highly dependent from NH_3 production, as acidification, particulate matter formation and terrestrial eutrophication, the contribution of heifer and calves ranged from 30 to 45%. The type of manure produced may influence this result. Indeed, replacement animals were often reared on litter based systems, which potentially increase GHG emissions (Hou et al., 2015). The shift towards slurry based system also for these animal categories, followed by proper managing of storages and manure spreading, could help improve the environmental impact of the replacement herd.

4. Conclusions

Measured and estimated calculation approaches led to different LCA results. In particular, the global warming impact seemed to be underestimated by the IPCC equations. This method, developed to

compile national inventories, is unlikely to accurately approximate the emissions from manure management if applied to a specific dairy farm. More experimental data are needed to make emission factors (MCF and EF_3) more precise and flexible in order to place estimations closer to the actual level of emissions. Detailed data from representative manure systems are needed to guide climate change mitigation strategies. On the other hand, NH_3 related impact categories showed a higher values if they were calculated using the estimated approach, underling that a safer level of estimation was maintained. The innovative approach of this study allowed to underline the share of environmental impact from different animal categories. A large part of environmental impact comes from unproductive and young animals, for this reason management choices for housing and feeding of these animals can be crucial for the sustainability of the whole milk production process.

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